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EVALUATION OF THE RELATIVE HYDROGEN EMBRITTLEMENT SUSCEPTIBILITY OF ESR 4340 AND ITS HEAT TREAT DISTORTION PROPERTIES

September 1982

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ABSTRACT

A test program to compare the relative hydrogen embrittlement susceptibility of remelted 4340 steel with ESR and VAR methods has been completed. The issue of ESR's susceptibility to hydrogen embrittlement arose when unexpected difficulties were experienced with critical control system actuator pistons on the helicopter programs. High strength (above 260 Ksi) 4340 ESR steel is used in these applications because of 4340 ESR's demonstrated superior ballistic tolerance.

Three heat treat levels and two grain orientations were evaluated; and three test methods were applied to measure embrittlement susceptibility. A significant reduction in embrittlement susceptibility is associated with lower strength (~43 HRC) as compared to high strength (~53 HRC) 4340. The short transverse grain direction is more susceptible than the longitudinal direction, and all test methods indicated that VAR is less susceptible to hydrogen embrittlement than ESR.

A parallel effort during the test program focused on heat treat distortion differences between ESR and VAR 4340. While a difference in distortion propensity cannot be ruled out on the basis of test results, it can be concluded that such differences between ESR and VAR are small compared to heat treatment parameters affecting distortion.

FINAL REPORT

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1.0 ABSTRACT

A test program to compare the relative hydrogen embrittlement susceptibility of remelted 4340 steel with ESR and VAR methods has been completed. The issue of ESR's susceptibility to hydrogen embrittlement arose when unexpected difficulties were experienced with critical control system actuator pistons on Army helicopter programs. High strength (above 260 Ksi) 4340 ESR steel is used in these applications because of 4340 ESR's demonstrated superior ballistic tolerance.

Three heat treat levels and two grain orientations were evaluated; and three test methods were applied to measure embrittlement susceptibility. A significant reduction in embrittlement susceptibility is associated with lower strength (~43 HRC) as compared to high strength (~53 HRC) 4340. The short transverse grain direction is more susceptible than the longitudinal direction, and all test methods indicated that VAR is less susceptible to hydrogen embrittlement than ESR.

A parallel effort during the test program focused on heat treat distortion differences between ESR and VAR 4340. While a difference in distortion propensity cannot be ruled out on the basis of test results, it can be concluded that such differences between ESR and VAR are small compared to heat treatment parameters affecting distortion.

2.0 PERTINENT RESULTS FROM TASK I

Results from Task I of this test program were submitted September 1, 1981, in the form of an Interim Report, plus a supplement thereto on October 30, 1981. For task I, five different forms of 4340 steel were evaluated, one air melt, two ESR and two VAR. Pertinent results from Task I are summarized below:

a) At low strength levels (180 - 200 Ksi) all of the tested materials appear relatively immune to hydrogen embrittlement.

b) At high strength levels (above 260 Ksi) ESR appears intermediate in hydrogen embrittlement susceptibility between air and vacuum melted 4340 types of steel. (See Figure 2.3).

c) The Notched Round Bend (NRB) test method per ASTM F519-77, Type 1c, using cadmium plated test coupons, is an effective means of testing for hydrogen embrittlement susceptibility for high strength applications (above 260 Ksi).

d) Measurements of residual hydrogen showed such irregular results that the repeatability of measurements and the usefulness of such measurements needs to be questioned.

e) The test results from Task I of the program are summarized in Figures 2.1, 2.2, 2.3 and 2.4.

Figure 2.1 shows the relative notched tensile strength of the 9 conditions tested, which included 5 materials and two hardness ranges (nominally 43 HRC and 53 HRC). The NTS/UTS ratio was about 1.5 for the 43 HRC steels and about 1.2 for the 53 HRC steels.

Figure 2.2 shows the relative notched strength in bending in units of "number-of-turns-to-fracture" (NOTF) for five steels at the high hardness level, i.e., 53 HRC. All specimens were plated except for one specimen in condition "B". The sustained load used in the time-to-failure (TTF) tests varied with each material and is indicated by the dashed line, which represents 0.75 NOTF.

Figure 2.3 shows the differences in TTF for each of the high hardness steels that were put under a sustained load. Each bar represents one specimen. The VAR steels show a definite improvement above the ESR steels with regards to hydrogen embrittlement cracking.

Figure 2.4 illustrates the significant degradation due to the introduction of hydrogen into the steel during cadmium plating per QQ-P-416C. Without plating, slightly more than 12 turns are required to fracture the specimen. Only 6 turns will fracture

the specimen that has been plated. At a sustained load of 5 turns, the plated specimen breaks in less than 10 minutes; whereas the unplated specimen continues to run for greater than 10,000 minutes. When the load is increased to 9-turns, the specimen that was not plated, does not fracture even after 57,000 minutes. In fact, the specimen could not be fractured below the ultimate load determined in the initial fracture test. The purpose of this series of tests was to clearly illustrate the extent of strength degradation caused by residual mobile hydrogen introduced into the steel during the plating operation.

FIGURE 2.1

Notched Round Tensile Strength of Nine Conditions Tested

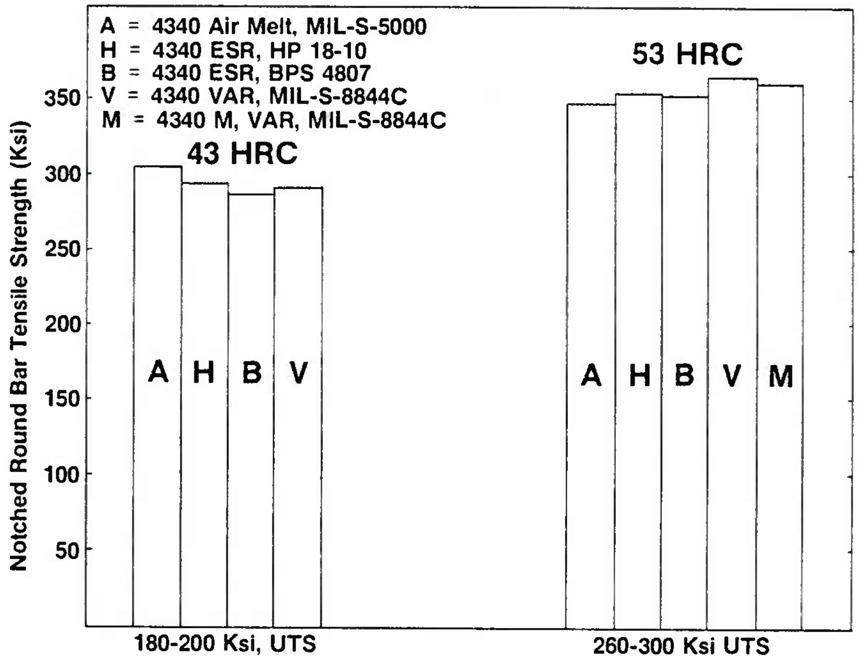


FIGURE 2.2

Notched Round Bend Strength
of Five High-Strength Conditions Tested

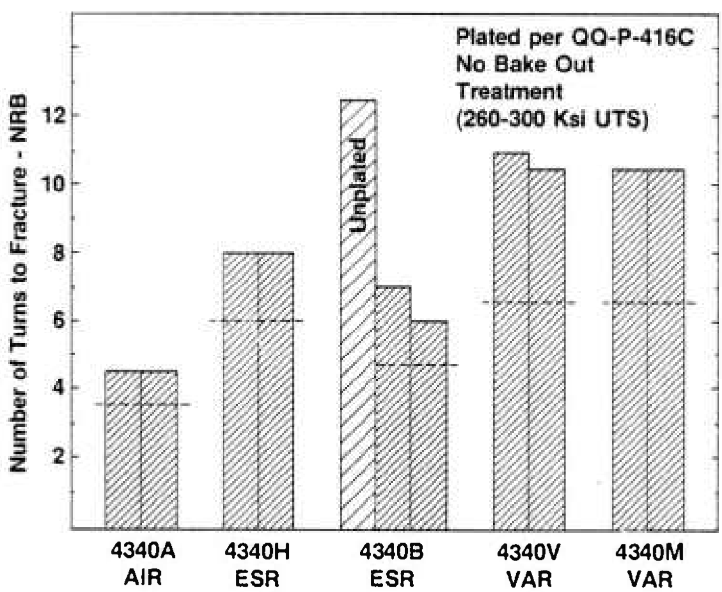


FIGURE 2.3

Time To Failure for High Strength Bend Specimens

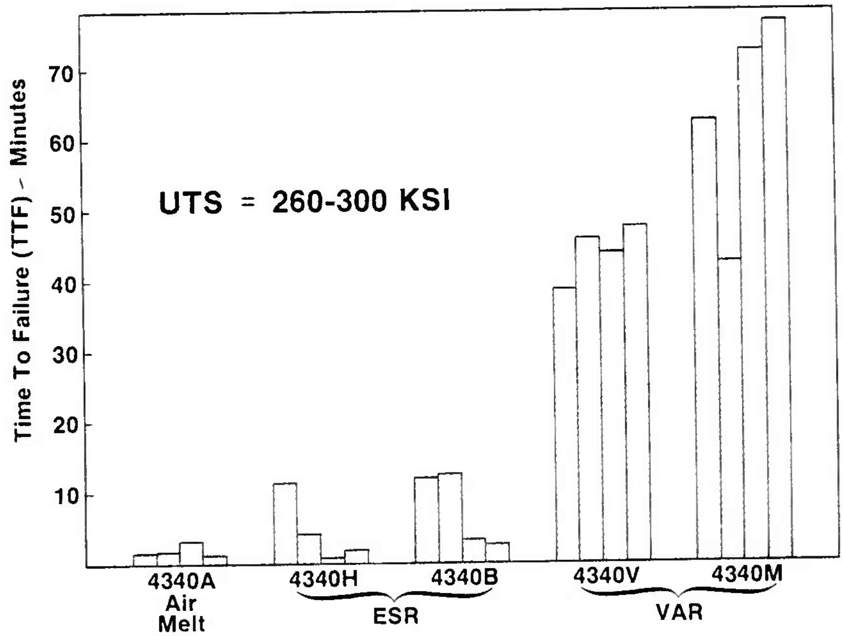
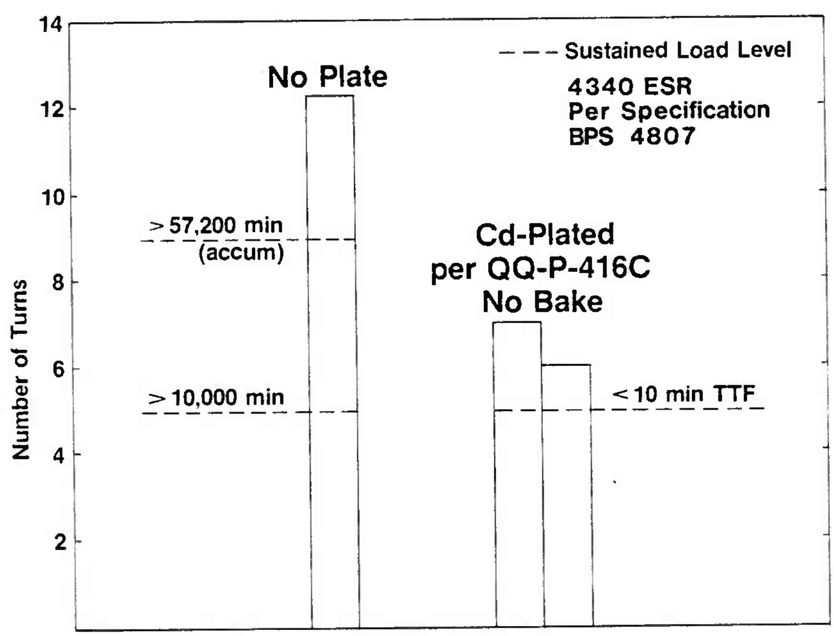


FIGURE 2.4

Degradation in Strength of 4340B Steel Due to Cd-Plating



3.0 OBJECTIVES FOR TASK II

While Task I compared five unrelated types of 4340, produced to different specifications, Task II is aimed at evaluating 4340 steel which is treated identically in every way except for the remelting process, ESR versus VAR. That is, the ESR steel and the VAR steel were derived from the same starting Argon Oxygen Degassed (AOD) ingot. Machining of test coupons, heat treating, processing and testing were conducted so as to assure equal treatment of ESR and VAR such that test result variations between the two types of specimens could be legitimately attributed to the remelting process. The following characteristics were to be assessed:

A) Susceptibility to Hydrogen Embrittlement

- Considering three strength ranges
- Considering two grain orientations
- Using three test methods

B) Heat Treat Distortion

- Using two heat treat procedures

4.0 MATERIAL AND PROCESSING

Steel used for Task II of the test program was furnished by the Army. Mechanical properties and chemical data are summarized below.

4.1 Mechanical Properties

TABLE 4.1

Mechanical Properties of 4340 Steel*

	.2% YS KSI	UTS KSI	% EL	% RA
VAR 5 in. sq.	233	271	12	43
ESR 5 in. sq.	236	273	13	47
VAR 8 in. sq.	230	269	13	45
ESR 8 in. sq.	227	268	13	47
VAR 5 in. X 12 in.	234	271	12	44
ESR 5 in. X 12 in.	232	269	11	44
VAR 2.5 in. dia.	232	272	12	47
ESR 2.5 in. dia.	234	276	14	48

* Average of four - transverse orientation.
Yield strength at .2% offset.
Tempering temperature was 475F.

4.2 Chemistry

TABLE 4.2

Chemical Composition, wt. % of 4340 Steel

	HEAT NO.	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Al	N	O	H ppm
ACD	8652106	.42	.66	.007	.001	.24	.19	1.73	.94	.22	.032	--	--	--
ESR	3710046	.41	.70	.008	.001	.26	.21	1.73	.90	.22	.035	.008	.004	1.8
VAR	3841687	.42	.46	.009	.001	.28	.19	1.74	.89	.21	.031	.005	.001	1.0

4.3 Independent Analysis of Hydrogen in Steel

Prior experience with hydrogen counts has suggested that they may not be as reliable and repeatable as one would hope. For this reason special samples were submitted to a test laboratory in the Los Angeles area for a check on the hydrogen concentration of the steel as received. The selected laboratory uses a Leco RH-2 machine, which measures hydrogen by inert gas fusion and thermal conductivity.

A section of 2.5 inch diameter bar was turned down to approximately 1.125 inch diameter for both the ESR and VAR materials. These reduced bars were then cut into approximately four 1 inch length discs and identified by code as to their origin, i.e., ESR or VAR. Three ESR discs and two VAR discs were submitted for analysis on two different dates as shown:

TABLE 4.3

Hydrogen Count (PPM) Comparison

	Data From Supplier	Local Lab. 1-29-82	Local Lab. 2-22-82
ESR	1.8	1.9	1.1; .9
VAR	1.0	1.4	.4

When the laboratory was contacted regarding the results, they explained that more readings had been taken than reported on 2-22-82, since they knew a check was being run. The reported readings were at the center of each disc; some additional readings had been taken at the edge and at mid radius with the following results:

TABLE 4.4

Hydrogen Readings (PPM) Across Disc Face

	Disc Center	Mid Radius	Disc Edge
ESR	1.1	1.2	2.1
ESR	.9	1.1	--
VAR	.4	1.1	2.3

If the data in Table 4.4 is correct, it would indicate that hydrogen measurements are very location dependent, even in the case of coupons machined from the center of a round bar, without any further processing or heat treating exposure. It is also conceivable that measuring techniques are not as yet developed to the point where hydrogen measurements can consistently be depended upon.

4.4 Heat Treatment

The split VAR/ESR billets received from the steel producer were forged (Minimum reduction 3:1) in the range of 2100F to 1700F and supplied in the fully annealed condition. To achieve the high hardness range of 53 HRC, two heat treatments were applied. They were designated HP1-1 and BPS 4808.

BPS 4808	HP1-1
Normalize 1650F	Normalize 1650F
Temper 1250F	Temper 1200F
Salt Furnace Austenitize 1525F	Vacuum Furnace Austenitize 1525F
Salt Quench 325F or/Oil Quench agitated 225-280F	Oil Quench ~ 140F
Temper (3 Hours) 400-475F	Temper (4 Hours) 340F
UTS = 260-280 Ksi	UTS = 290-320 Ksi

Test parts heat treated to 180 - 200 Ksi followed the BPS 4808 procedure, except that the tempering temperature was in the 850F - 900F range.

5.0 HYDROGEN SUSCEPTIBILITY TESTS

5.1 Notched Round Tension (NRT) Potentiostatic Test Method

5.1.1 Experimental Approach

Similar to the work performed in Task I on five different heats of 4340 steel, notched round tensile bars with a threaded end as per Appendix A, Drawing 101780, were used to evaluate the susceptibility to hydrogen embrittlement of a split heat of 4340 steel at three hardness levels. Slight modifications in the test procedure were incorporated based on experience obtained in the Task I test program. The applied dead weight or sustained load was at 75% of the notched tensile strength instead of 90% as previously applied. In addition, the test potential range was limited to -0.9 to -1.1 volts vs SCE (Standard Calomel Electrode) in order to restrict the failure mode to one of hydrogen embrittlement. A 3.5% saltwater solution was used as the environment.

The loading sequence consisted of installing the NRT test coupon into a Satec 12-Kip sustained load creep frame with a very light load. The saltwater solution was inserted into the Lucite container surrounding the test coupon. A level of the solution was maintained just below the notch area. At this point, the Standard Calomel, reference, and working electrodes were connec-

ted and the potential adjusted to the desired value. Once the potential was maintained, more solution was added until the level was above the notch; i.e., covered the notch. The 0.75NTS load was then applied. At no time did the saltwater solution come in contact with the upper threaded portion of the test sample. The lower thread was isolated from the environment. The front view of the test assembly, including the Lucite container, test specimens, and reference electrodes are seen in Figs. 5.1 and 5.2; and from the rear view of the assembly, the potentiostat, multimeter, and dead weight loading assembly are seen in Figs. 5.3 and 5.4.

The test program consisted of running three notched tensile coupons for each of six conditions in order to establish the NTS. The susceptibility to hydrogen embrittlement was then measured by recording the time-to-failure (TTF) in the saltwater environment with the cathodic potential applied. Longer times imply greater resistance to hydrogen embrittlement cracking.

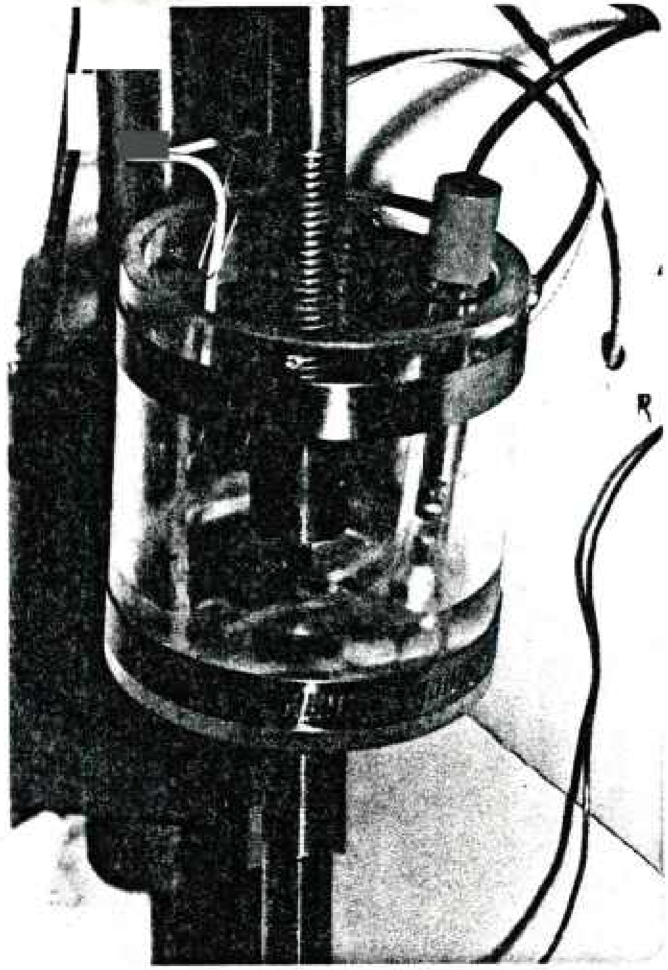


Figure 5.1
Lucite container
surrounding
NRT-specimen

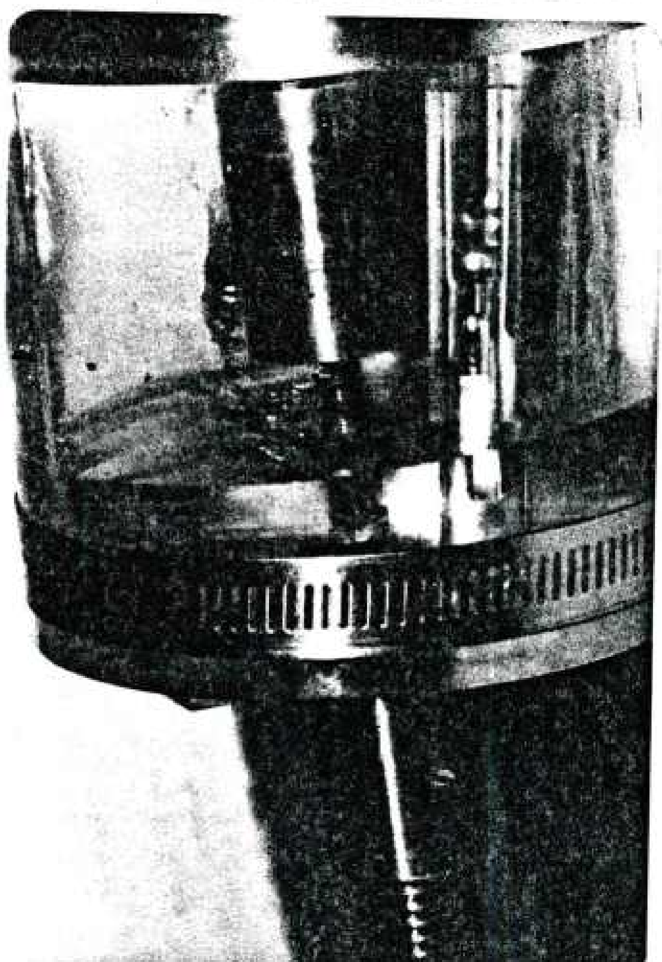


Figure 5.2
Notch submersed
in 3.5% salt water
solution

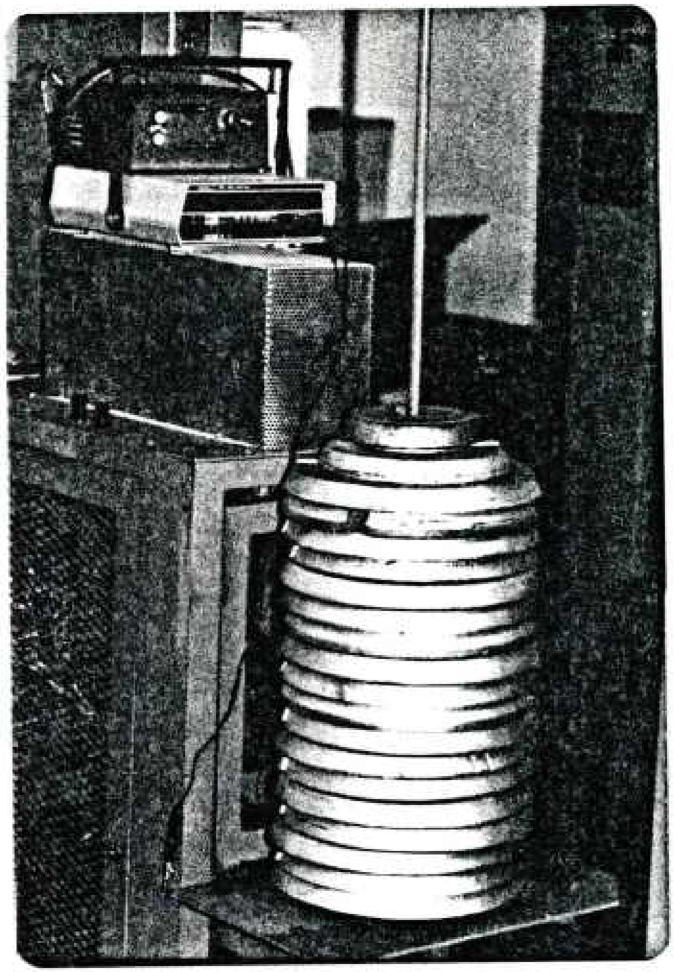


Figure 5.3
Potentiostat,
multimeter, and
dead-weight
load blocks.

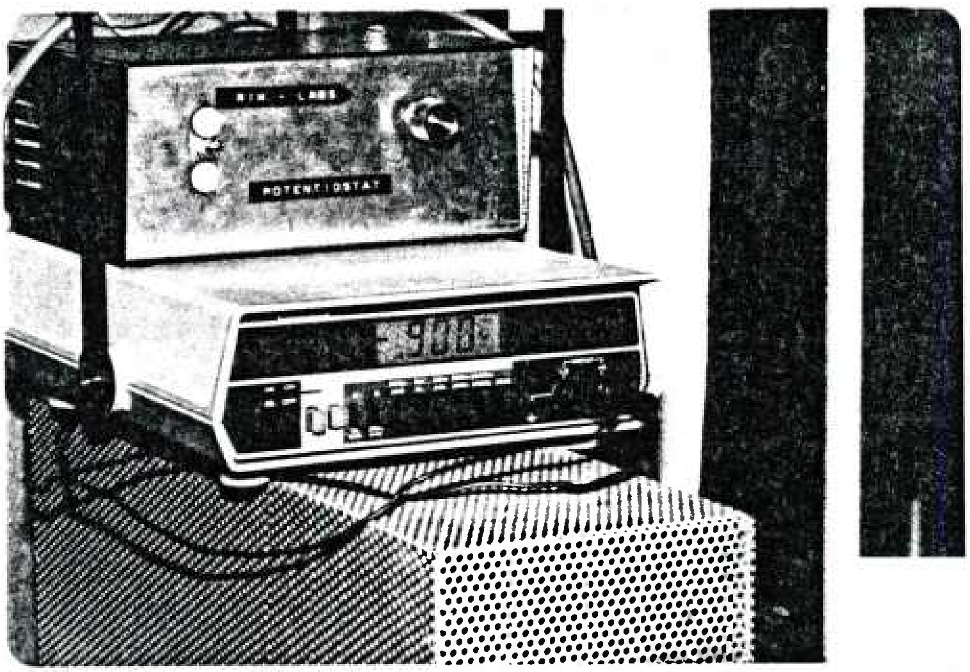


Figure 5.4
Potentiostat and
multimeter set
at-0.9 volts.

5.1.2 Results

The NTS, and TTF are summarized in Table 5.1. Two of the three lots from both the VAR and ESR ingots were heat treated to near 300 Ksi tensile strength range and one of the three lots from each ingot was heat treated to near 200 Ksi tensile strength range. Based on the ultimate breaking loads, 7500 pounds was selected as the sustained load level for 0.75NTS of all the high hardness loads of VAR/ESR steels. For the lower hardness steels, 5500 pounds was selected as the sustained load level of 0.75NTS.

TABLE 5.1

Hydrogen Susceptibility of Notched Round Tensile (NRT) Bar

MATERIAL SPEC.:	4340 VAR						4340 ESR					
Strength Level	Heat Treat Lot △	NTS (lbs)	0.75 NTS Load (lbs)	Time to Failure (mins) -0.9V	-1.0V	-1.1V	Heat Treat Lot △	NTS (lbs)	0.75NTS Load (lbs)	Time to Failure (mins) -0.9V	-1.0V	-1.1V
290-320 Ksi HP1-1	-11	A 9900 B 9650 C 10025	7500	E 546 F -- K 475 AVG 510	D 180 -- K 135 AVG 158	I 4.67 H 6.00 J 4.67 AVG 5.1	-5	A 9900 B 9850 C 9550	7500	D Ø H 619 F -- E -- AVG 619	G 74 -- I 96 AVG 85	J 1.91 K 1.25 L 2.5 AVG 1.9
260-290 Ksi BPS 4808	-9	A 9500 B 9400 C 9300	7500	D -- E -- F 624 AVG 624	G -- H 114 I 114 AVG 114	J -- K 1.5 L 7.5 AVG 4.5	-3	A 9350 B 9650 C 9600	7500	D 408 E 504 F 630 AVG 514	G 71 H 104 I 120 AVG 98	J 4.65 K 5.25 L 3 AVG 4.3
180-200 Ksi BPS 4808	-7	A 7500 B 7400 C 7500	5500	D 7512 E 3948 F 5664 AVG 5708	G 1476 H* L 1047 AVG1261	J 1068 K 1500 L1284 AVG1284	-1	A 7600 B 7350 C 7400	5500	D 3162 E 2604 F 4956 AVG 3574	G 672 H 900 I 1639 AVG1070	J 1176 K 1417 L 1830 AVG1474

D*: Potential turned off for 30s. Potential reapplied & timer reset.
J*: Potential not steady. Test discontinued after 1 1/2 min. Potentiostat problem.
H*: Corroded overnight and test stopped.
DØ: Broke in upper threads.
△: See Appendix A, Drawing 101780.

The test results were measured in minutes and are plotted on Figure 5.5 where the cathodic potential is on the vertical axis with a linear scale and TTF is on the horizontal axis with a logarithmic scale.

VAR is more resistant to hydrogen embrittlement at the highest cathodic potential (-1.1V) than ESR for the higher hardness (53 HRC). As the potential is decreased to -0.9V, the results appear to converge. For the lower hardness (43 HRC), the opposite appears to be true; i.e., VAR is more resistant than ESR at -0.9V and converges (or crosses) at -1.1V. No clear advantage exists with regard to the HP1-1 or BPS 4808 heat treatments.

5.2 Notch Round Bend (NRB) Cd-Plated Test Method

5.2.1 Experimental Approach

The contractor furnished machined NRB specimens as described in Appendix A, Drawing 101781. These specimens represented two different grain orientations from the split 4340 ESR/VAR ingot. The test orientations were longitudinal and short transverse. The notched round bend strength was measured by installing the bend specimen in a test fixture as described in the Task I

FIGURE 5.5

NRT Potentiostatic Test Results

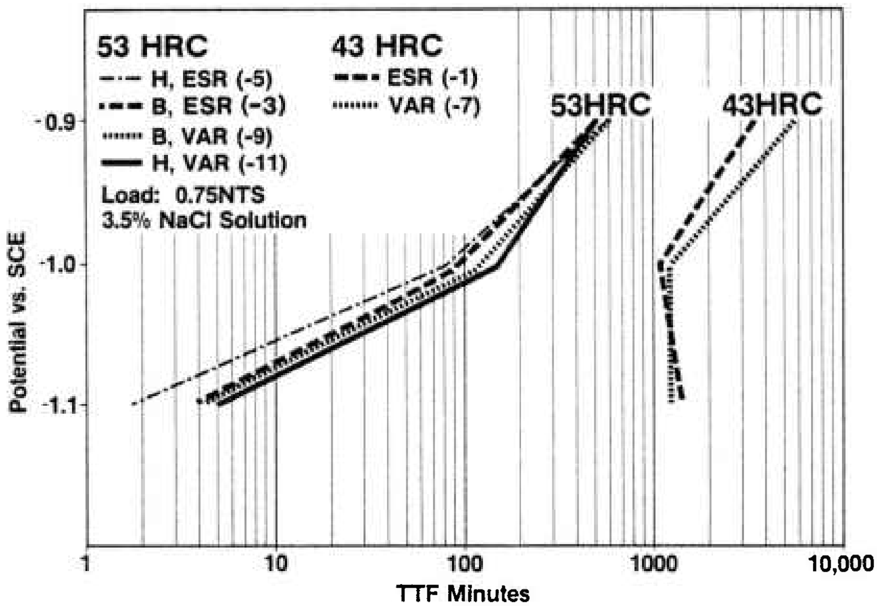
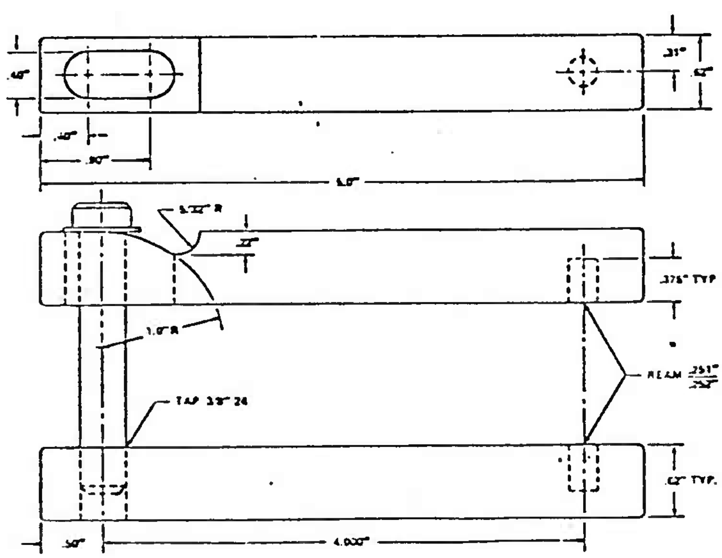


FIGURE 5.6

NRB-Loading Frame per ASTM F519-77 (Type 1C)



report. The number of turns to fracture one specimen, as-machined, with no surface treatments, was initially measured. Then a Cd-plated specimen that did not receive a hydrogen bake-out treatment, but instead a one hour, 300F homogenization treatment after plating per specification QQ-P-416C was also fractured. A fraction of the fracture load; i.e., six turns was used as sustained load during the TTF measurements. Figure 5.6 shows a typical NRB loading bar per ASTM standard F519-77 (Type lc).

5.2.2 Results

The notched round bend strength as measured in number of turns for both the unplated and plated specimens is shown in Figure 5.7. As noted, the introduction of hydrogen from the plating process does cause a degradation in the strength, which is more significant in the ESR ingot than in the VAR ingot. The observation applies to all conditions tested, which includes two strength levels and two test directions. The lower hardness heat treatment was not used in this phase of the program because of the Task I experience which showed the method best suited for the high hardness steels.

The susceptibility to hydrogen embrittlement in the NRB test fixture is illustrated in Figure 5.8 where the TTF in minutes is plotted on a bar graph for the four conditions tested. As noted, the longitudinal orientation appears to have more resis-

FIGURE 5.7

Notched Round Bend Strength for Cd-Plated and Unplated Specimens

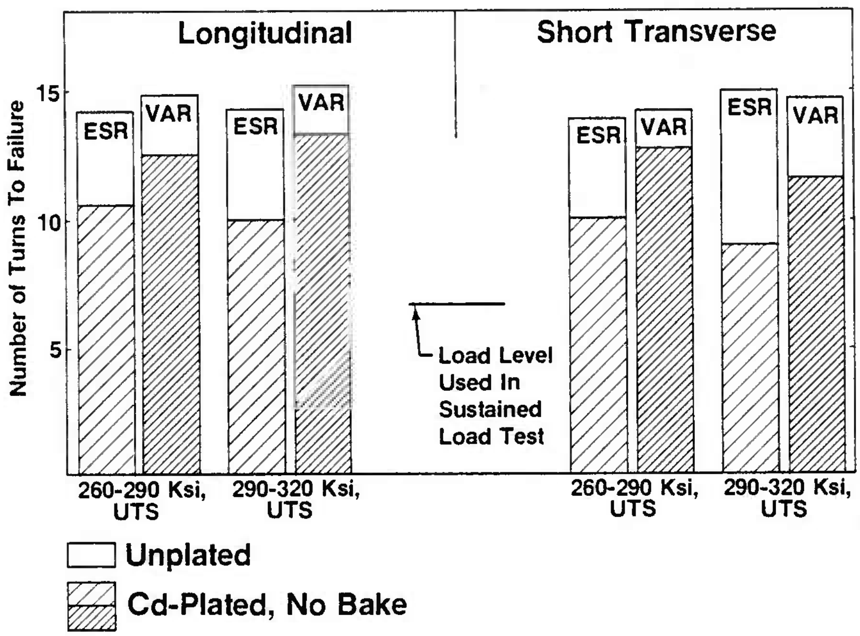
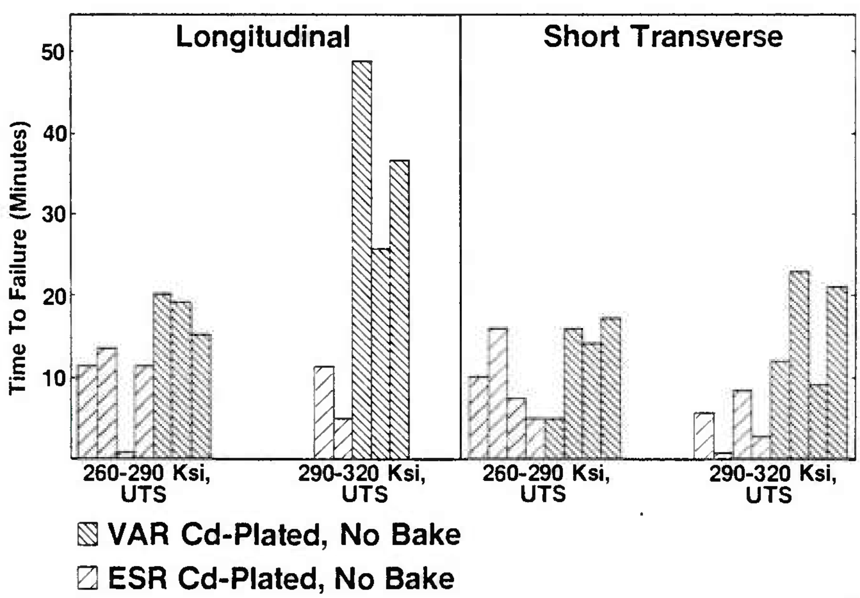


FIGURE 5.8

NRB-Sustained Load Test Results Loaded to 6-Turns in Air



tance to hydrogen embrittlement than the short transverse orientation. In all cases, the VAR ingot performs as well or better than the ESR ingot. No clear advantage exists between the HP1-1 or BPS 4808 heat treatments.

5.3 Notched Round Bending (NRB) Potentiostatic Test Method

5.3.1 Experimental Approach

A third test method was employed by using extra NRB specimens supplied by the contractor. The specimens were not Cd-plated, but instead were exposed to a hydrogen environment by using a potentiostatic method similar to that employed with the NRT specimens (Fig. 5.1). The variations in the test procedure was to apply a bending load instead of a tensile load. This was accomplished by modifying a special loading fixture developed at METTEK Laboratories for Charpy-sized specimens.

Two specimens for each of the eight conditions were used to conduct the program. One specimen was loaded to fracture in air and the number of pounds of force required to break the specimen was recorded via an instrumented bolt on the loading frame. The 3.5% saltwater solution was then added and a potential of -1.1 volts vs SCE was applied on the second sample for each of the eight conditions. A rising step load procedure is utilized. The test terminates when fracture occurs in the test environ-

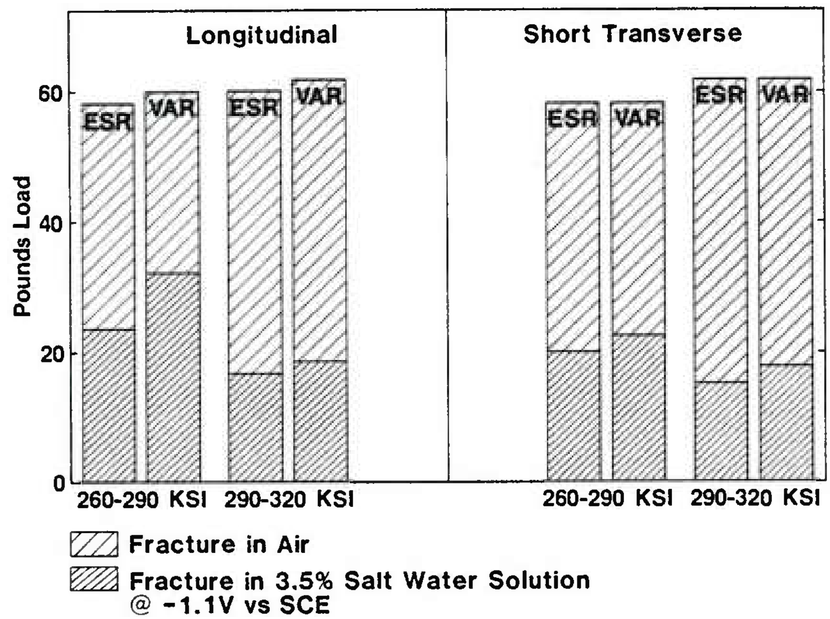
ment. The load required to cause fracture is then recorded and used as an index of susceptibility to hydrogen embrittlement cracking.

5.3.2 Results

Figures 5.9 illustrate the results as determined by the NRB potentiostatic test method. These results are similar to those presented in Figure 5.8 with the exception of the longitudinal ESR test coupon. In all cases, the VAR test specimens performed equal to or better then the ESR test specimens; but the differences are not as dramatic as those presented with the Cd-plated bend specimens, especially for the longitudinal 290-320 Ksi heat treatment. A heat treat advantage appears to exist with BPS 4808.

FIGURE 5.9

Notched Round Bending Potentiostatic Test Results



5.4 Discussion

5.4.1 NRT Potentiostatic Test

The sustained load notched tensile tests in a cathodically polarized saltwater environment, clearly establishes the advantages of a lower hardness (43 HRC) heat treat range (180-200 Ksi) above the higher hardness (53 HRC) heat treat range of (260-300 Ksi).

Closer examination of anomalously failed test coupons was performed in an attempt to explain some of the scatter in the test data. For example, sample 5D broke after 20 minutes in the upper thread as shown in Figure 5.10. Recalling that, the upper thread is not even immersed in the corrosive environment makes the failure difficult to explain. Based on a consideration of area differences alone, the stress in the threads is 1/8 the stress at the notch or .75NTS/8 equals approximately 0.1NTS. Needless to say, this behavior is unexplainable even after performing a failure analysis on the fracture face, which established that a thumbnail crack was caused by a hydrogen embrittlement as evidenced by the intergranular topography shown in Figure 5.11.

Another sample, 5E, from the same group had failed in an unusually short time and its fracture face is compared to that of 5D (Figs. 5.12 and 5.13). To be noted in this case is a longitudinal crack across the surface. At higher magnification the crack is seen to extend to the base of the notch as shown in Figures 5.14. Cracks of this type could conceivably be introduced during the 3 to 1 reduction during forging the ingot in the temperature range of 2100F to 1700F. This delamination or hot tear crack would provide an easy access path for the hydrogen being cathodically generated at the surface of the NRT specimen.

Figure 5.10
NRT sample 5D,
broke in threads.

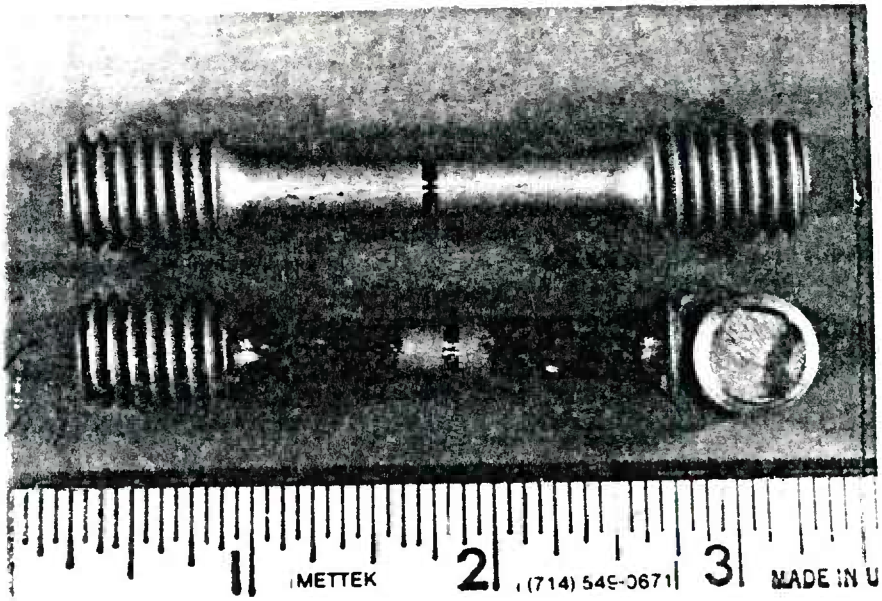


Figure 5.11
Sample 5D,
hydrogen
embrittlement
crack.

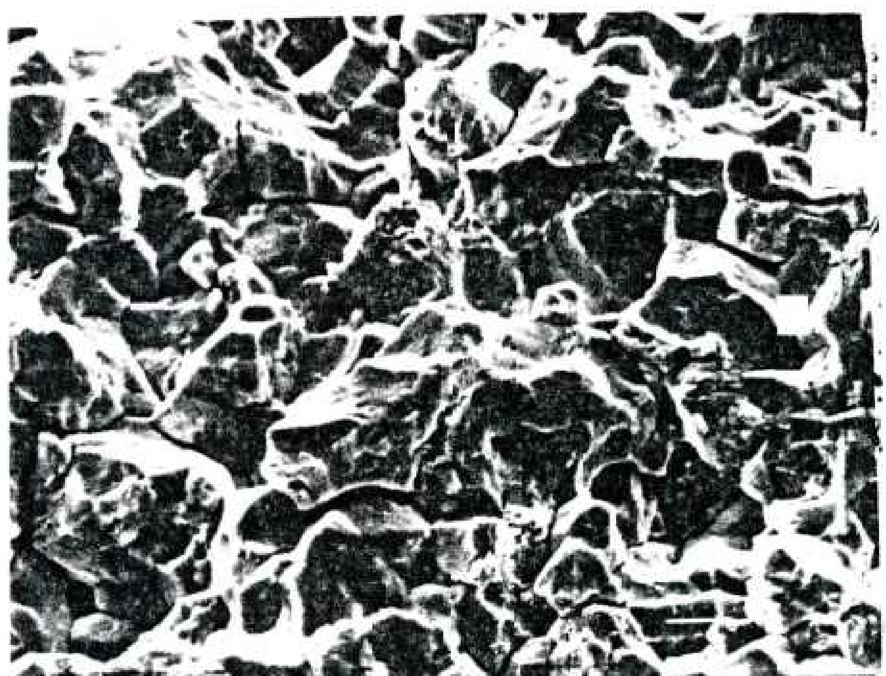


Figure 5.12
Macrosection of
Sample 5D
fracture face.

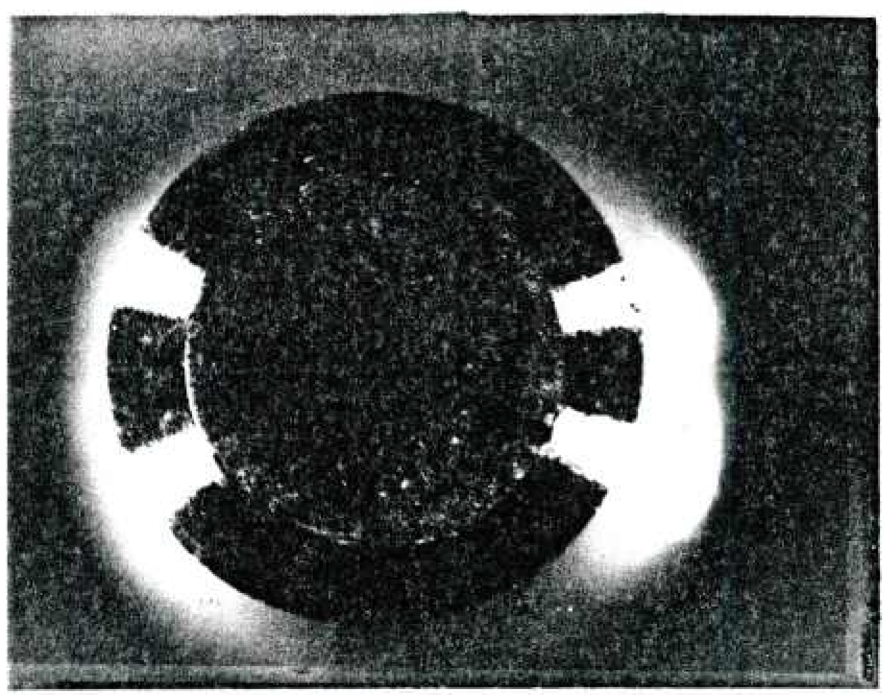
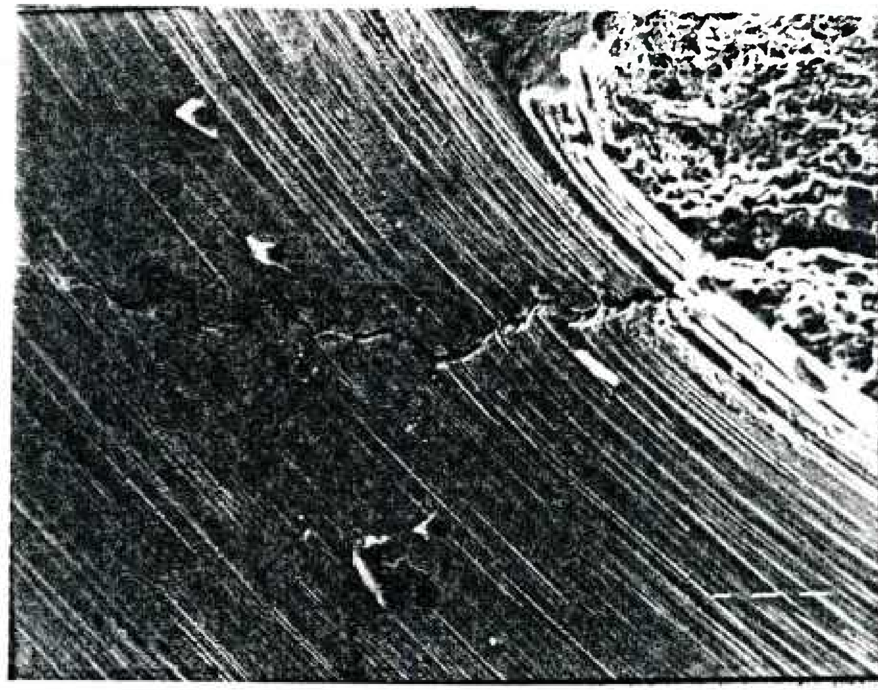


Figure 5.13
Macrosection of
Sample 5E
fracture face.

Figure 5.14
Longitudinal
delamination or hot
tear in Sample 5E
at notch.



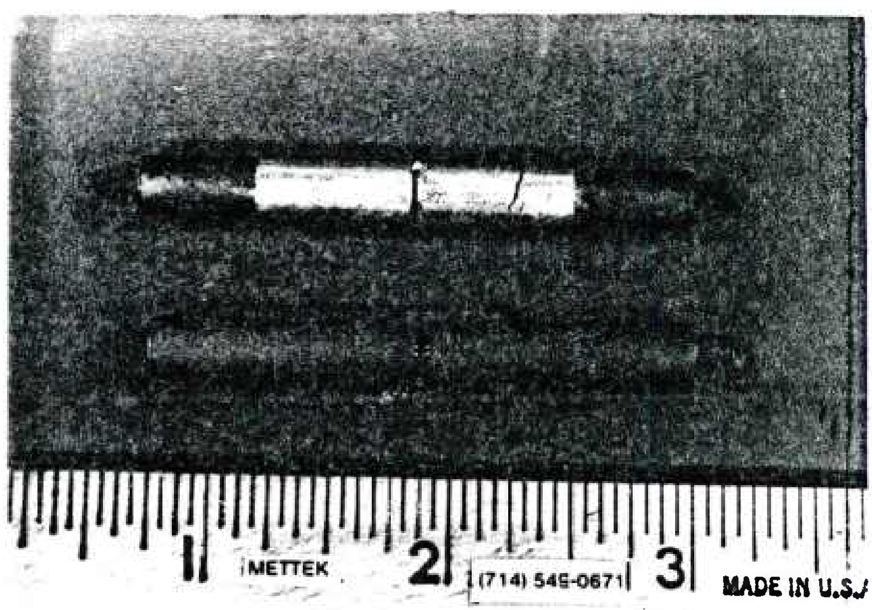


Figure 5.15
NRB plated samples
that failed in the
shank.

5.4.2 NRB Cd-Plated Test Method

The notch round bend test results also had anomalies which apparently affected the degree of scatter; but the results appear to be more consistent than the time-to-failure tests with the cathodically applied potential. Figure 5.15 shows a VAR specimen, which under a pure bending load did not break in the notch as expected but instead broke in the shank as indicated in the Figure. Although most specimens do break where the stress is highest. It may be stated that there are apparently parameters that on occasion are more significant than the state of stress. Regarding advantages of one remelt process over the other, the VAR is found to be consistently less susceptible to embrittlement than ESR.

5.4.3 NRB Potentiostatic Test Method

This method gave results similar to the Cd-plated method except for the fact that the differences appear to be less dramatic. The pattern is consistent, although the loads as an index for hydrogen embrittlement susceptibility show smaller differences.

6.0 HEAT TREAT DISTORTION TEST

6.1 Background

The purpose of this test is to determine if 4340 ESR steel has a greater tendency towards heat treat distortion than VAR steel. This issue arose during the early production runs of control actuator piston rods. The experienced distortion was such that a number of pistons fractured during the straightening operation following heat treatment. At this time quench cracks were also observed in some of the piston rods.

As a solution to these problems the heat treater suggested a change from the specified vacuum austenitizing to salt austenitizing. The latter would permit a warmer quenching medium (salt or oil) in lieu of the 140F oil required for vacuum austenitizing. (Oil above 140F tends to vaporize when exposed to vacuum.) As these recommendations were followed, the heat treat distortions became acceptable and the quench cracks disappeared.

The question remained, however, whether or not the problems encountered were associated with the use of ESR steel, since both the heat treater and production personnel could not recall experiencing such severe distortion and cracking problems on similarity configured hardware which did not use ESR steel.

6.2 Experimental Approach

To simulate a typical control actuator piston rod, a twelve inch long test specimen was designed (See Appendix A, Drawing 101782). A total of 40 such test samples were fabricated, 20 from ESR steel and 20 from VAR steel. Machining was tightly controlled, such that the runout before heat treatment was less than .003 inches TIR (Total Indicator Reading).

The forty specimens were then divided into two groups, designated Lot 1 and Lot 2, each lot consisting of 10 specimens ESR and 10 specimens VAR. The twenty specimens in a particular lot, ten ESR and ten VAR, would then be subjected to heat treatment as a batch. TIR readings were recorded before and after heat treatment, the difference being the heat treat distortion.

Readings were taken at three locations along every specimen. For each of the three locations an average distortion value was determined for the ESR and VAR pistons in the two lots. The results are shown in Figures 6.1 and 6.2.

For Lot 1, instructions to the heat treater were initially misinterpreted. Instead of vacuum austenitizing, an endothermic furnace was used. Results were recorded and are included in Figure 6.1. Before subjecting the Lot 1 specimens to the vacuum heat treatment, the specimens were tempered to 160 - 180 Ksi and turned slightly undersize to reestablish straightness.

FIGURE 6.1

Heat Treat Distortion of Lot 1

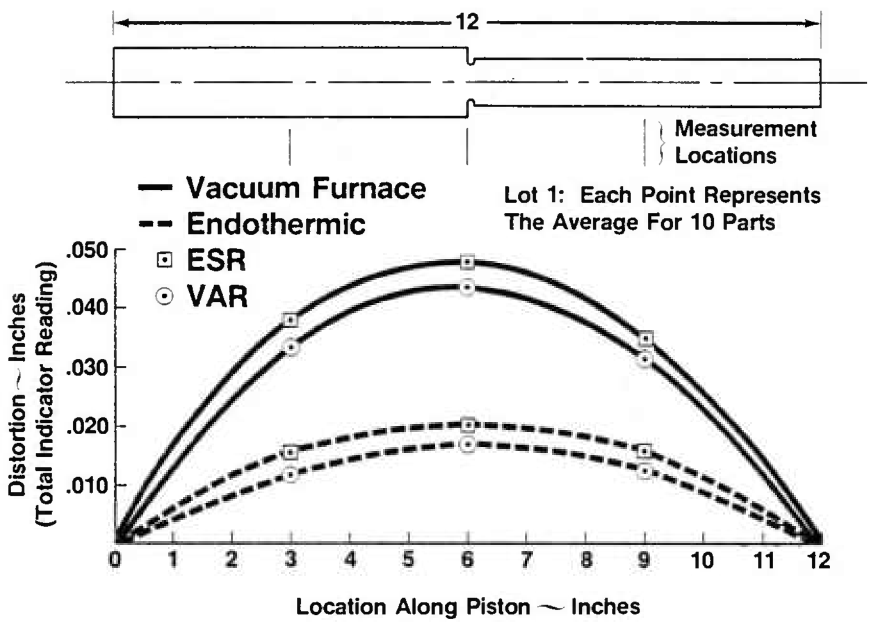
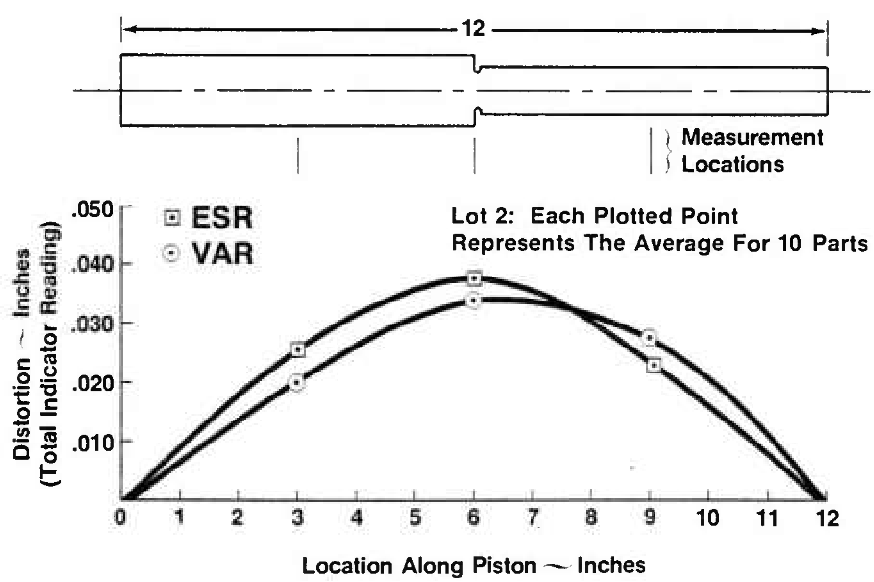


FIGURE 6.2

Heat Treat Distortion of Lot 2



6.3 Results

Figure 6.1 shows that when distortion measurements were averaged for Lot 1, ESR steel exhibited slightly more distortion than VAR, both for endothermic and vacuum heat treating. The difference in these averaged values is typically in the 10 to 20% range. For Lot 2 the results show a similar trend for two out of the three measured locations, but for the third location the trend actually reversed, showing greater distortion for VAR then ESR.

Average values had to be plotted, since individual distortions varied greatly from part to part as is shown in Tables 6.1 through 6.6.

6.4 Discussion

While in total the distortion data suggests that ESR steel distorts more than VAR, the difference between the two when averaged is rather small, and even reversed at one measurement location. Considering also the rather large variations in distortion from part to part for both ESR and VAR steels leads to the conclusion that factors other than the remelt process (i.e., ESR or VAR) are important in determining the distortion characteristics of the parts.

Looking at Figure 6.1 a more significant factor affecting distortion is suggested. The heat treatment using an endothermic furnace produced less than one half the distortion than the vacuum heat treating for either Lot 1 or Lot 2 parts. The quenching medium was 130F oil for both heat treating methods. The likely cause for the difference in distortion magnitude appears to be the time factor between when the furnace is first opened (or was backflushed with nitrogen in the case of the vacuum furnace) and when the parts entered the quenching bath. In the case of the endothermic furnace the time is reported as 13 seconds and for the vacuum furnace as 5 seconds. The increased delay time allows for additional cooling from the austenitizing temperature and thereby reduces the quench severity.

Such an explanation is consistent with the heat treater's contention that the steel has a "harder" as-quenched hardness with the vacuum furnace. Also, as mentioned in Paragraph 6.1, early in the production program heat treat distortion and quench cracking were brought under control by changing from vacuum heat treating to salt furnace ausenitizing. In the case of salt austenitizing, not only was there a quench delay time similar to that for the endothermic furnace, but the quenching medium was 220F or higher. Both of these factors would reduce distortion associated with temperature gradients.

The rather large distortion differences among parts from the same heat treating batch might be related to their relative position in the metal rack used for suspending the parts vertically. Since 20 pistons were heat treated simultaneously, those positioned on the outside of the rack may have been cooled more quickly or unevenly than those shielded on all sides by adjacent parts.

TABLE 6.1

HEAT TREATMENT DISTORTION MEASUREMENTS

Lot 1, ESR Specimens, Endothermic Heat Treat

SPECIMEN SERIAL NUMBER	MEASUREMENT LOCATION A			MEASUREMENT LOCATION B			MEASUREMENT LOCATION C		
	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.
1	.0002	.0086	.0084	.0001	.0030	.0029	.0003	.0080	.0077
2	.0005	.0100	.0095	.0007	.0085	.0078	.0004	.0055	.0051
3	.0007	.0152	.0145	.0010	.0261	.0251	.0005	.0208	.0203
4	.0001	.0175	.0174	.0003	.0220	.0217	.0005	.0145	.0140
5	.0003	.0300	.0297	.0004	.0365	.0361	.0005	.0270	.0265
6	.0002	.0075	.0073	.0006	.0095	.0089	.0008	.0092	.0084
7	.0006	.0230	.0224	.0007	.0275	.0268	.0008	.0220	.0212
8	.0003	.0182	.0179	.0003	.0202	.0199	.0004	.0155	.0151
9	.0005	.0072	.0067	.0006	.0150	.0144	.0005	.0072	.0067
10	.0001	.0298	.0297	.0005	.0370	.0365	.0008	.0368	.0360
	AVERAGE DISTORTION: .0164 STANDARD DEVIATION: .0083			AVERAGE DISTORTION: .0200 STANDARD DEVIATION: .0110			AVERAGE DISTORTION: .0161 STANDARD DEVIATION: .0094		

TABLE 6.2

HEAT TREATMENT DISTORTION MEASUREMENTS

Lot 1, VAR Specimens, Endothermic Heat Treat

SPECIMEN SERIAL NUMBER	MEASUREMENT LOCATION A			MEASUREMENT LOCATION B			MEASUREMENT LOCATION C		
	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.
1	.0002	.0065	.0063	.0003	.0097	.0094	.0005	.0087	.0082
2	.0004	.0140	.0136	.0008	.0180	.0172	.0005	.0148	.0143
3	.0006	.0100	.0094	.0007	.0087	.0080	.0010	.0042	.0032
4	.0006	.0095	.0089	.0012	.0245	.0233	.0010	.0188	.0178
5	.0008	.0128	.0120	.0009	.0080	.0071	.0008	.0020	.0012
6	.0006	.0228	.0222	.0008	.0268	.0260	.0010	.0200	.0190
7	.0006	.0153	.0147	.0010	.0230	.0220	.0015	.0185	.0170
8	.0005	.0013	.0008	.0005	.0113	.0108	.0010	.0178	.0168
9	.0004	.0218	.0214	.0006	.0320	.0314	.0005	.0251	.0246
10	.0007	.0130	.0123	.0014	.0171	.0157	.0012	.0080	.0068
	AVERAGE DISTORTION: .0122 STANDARD DEVIATION: .0061			AVERAGE DISTORTION: .0171 STANDARD DEVIATION: .0079			AVERAGE DISTORTION: .0129 STANDARD DEVIATION: .0072		

TABLE 6.3

HEAT TREATMENT DISTORTION MEASUREMENTS

Lot 1, ESR Specimens, Vacuum Heat Treat

SPECIMEN SERIAL NUMBER	MEASUREMENT LOCATION A			MEASUREMENT LOCATION B			MEASUREMENT LOCATION C		
	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.
1	.0006	.0318	.0312	.0005	.0355	.0350	.0005	.0190	.0185
2	.0005	.0512	.0507	.0007	.0612	.0605	.0007	.0435	.0428
3	.0009	.0418	.0409	.0018	.0495	.0477	.0013	.0280	.0267
4	.0007	.0562	.0555	.0009	.0705	.0696	.0008	.0498	.0490
5	.0007	.0375	.0368	.0007	.0475	.0468	.0015	.0358	.0343
6	.0005	.0543	.0538	.0006	.0712	.0706	.0005	.0502	.0497
7	.0010	.0345	.0335	.0011	.0545	.0534	.0012	.0536	.0524
8	.0002	.0332	.0330	.0004	.0490	.0486	.0008	.0425	.0417
9	.0003	.0360	.0357	.0005	.0388	.0383	.0005	.0253	.0248
10	.0009	.0090	.0081	.0018	.0048	.0030	.0016	.0038	.0022
	AVERAGE DISTORTION: .0379 STANDARD DEVIATION: .0130			AVERAGE DISTORTION: .0474 STANDARD DEVIATION: .0186			AVERAGE DISTORTION: .0342 STANDARD DEVIATION: .0152		

TABLE 6.4

HEAT TREATMENT DISTORTION MEASUREMENTS

Lot 1, VAR Specimens, Vacuum Heat Treat

SPECIMEN SERIAL NUMBER	MEASUREMENT LOCATION A			MEASUREMENT LOCATION B			MEASUREMENT LOCATION C		
	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.
1	.0003	.0465	.0462	.0008	.0580	.0572	.0010	.0432	.0422
2	.0004	.0461	.0457	.0014	.0568	.0554	.0013	.0432	.0419
3	.0008	.0358	.0350	.0012	.0481	.0469	.0010	.0322	.0312
4	.0017	.0440	.0423	.0027	.0538	.0511	.0020	.0352	.0332
5	.0005	.0338	.0333	.0011	.0362	.0351	.0010	.0262	.0252
6	.0004	.0502	.0498	.0010	.0650	.0640	.0008	.0512	.0504
7	.0010	.0268	.0258	.0010	.0430	.0420	.0009	.0515	.0506
8	.0012	.0251	.0239	.0014	.0365	.0351	.0014	.0191	.0177
9	.0005	.0115	.0110	.0015	.0110	.0095	.0013	.0038	.0025
10	.0002	.0315	.0313	.0002	.0360	.0358	.0003	.0260	.0257
	AVERAGE DISTORTION: .0344 STANDARD DEVIATION: .0114			AVERAGE DISTORTION: .0432 STANDARD DEVIATION: .0148			AVERAGE DISTORTION: .0321 STANDARD DEVIATION: .0143		

TABLE 6.5

HEAT TREATMENT DISTORTION MEASUREMENTS

Lot 2, ESR Specimens, Vacuum Heat Treated

SPECIMEN SERIAL NUMBER	MEASUREMENT LOCATION A			MEASUREMENT LOCATION B			MEASUREMENT LOCATION C		
	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.
11	.0002	.0035	.0033	.0004	.0060	.0056	.0004	.0065	.0061
12	.0007	.0250	.0243	.0013	.0450	.0437	.0012	.0230	.0218
13	.0003	.0250	.0247	.0001	.0400	.0399	.0001	.0301	.0300
14	.0001	.0305	.0304	.0003	.0410	.0407	.0011	.0285	.0274
15	.0007	.0265	.0258	.0010	.0420	.0410	.0003	.0230	.0227
16	.0002	.0380	.0378	.0005	.0770	.0765	.0004	.0310	.0306
17	.0001	.0300	.0299	.0005	.0380	.0375	.0004	.0210	.0206
18	.0008	.0085	.0077	.0008	.0140	.0132	.0004	.0140	.0136
19	.0003	.0310	.0307	.0007	.0380	.0373	.0004	.0255	.0251
20	.0007	.0314	.0307	.0011	.0435	.0424	.0011	.0259	.0248
	AVERAGE DISTORTION: .0245 STANDARD DEVIATION: .0103			AVERAGE DISTORTION: .0378 STANDARD DEVIATION: .0179			AVERAGE DISTORTION: .0223 STANDARD DEVIATION: .0071		

TABLE 6.6

HEAT TREATMENT DISTORTION MEASUREMENTS

Lot 2, VAR Specimens, Vacuum Heat Treated

SPECIMEN SERIAL NUMBER	MEASUREMENT LOCATION A			MEASUREMENT LOCATION B			MEASUREMENT LOCATION C		
	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.	INITIAL TIR	FINAL TIR	HEAT TR DIST.
11	.0004	.0087	.0083	.0007	.0245	.0238	.0006	.0245	.0239
12	.0004	.0220	.0216	.0006	.0340	.0334	.0003	.0280	.0277
13	.0005	.0138	.0133	.0011	.0140	.0129	.0011	.0090	.0079
14	.0003	.0272	.0269	.0004	.0423	.0419	.0006	.0388	.0382
15	.0005	.0150	.0145	.0006	.0295	.0289	.0003	.0234	.0231
16	.0005	.0020	.0015	.0010	.0110	.0100	.0008	.0130	.0122
17	.0006	.0360	.0354	.0010	.0538	.0528	.0007	.0458	.0451
18	.0010	.0263	.0253	.0015	.0388	.0373	.0016	.0270	.0254
19	.0002	.0380	.0378	.0005	.0605	.0600	.0005	.0465	.0460
20	.0005	.0241	.0236	.0007	.0368	.0361	.0008	.0254	.0246
	AVERAGE DISTORTION: .0208 STANDARD DEVIATION: .0109			AVERAGE DISTORTION: .0337 STANDARD DEVIATION: .0150			AVERAGE DISTORTION: .0274 STANDARD DEVIATION: .0120		

7.0 SUMMARY AND CONCLUSIONS

7.1

The three different test methods that were employed to evaluate the relative susceptibility of 4340 ESR/VAR to hydrogen embrittlement were consistent with varying degrees of sensitivity. In addition, direct measurement of the notched round bend strength Cd-plated specimens was also consistent with the results of the sustained load tests.

7.2

In all cases, VAR is shown to be more resistant than ESR with regard to hydrogen embrittlement cracking in 4340 steel.

7.3

There is no question as to the advantage of a lower hardness heat treatment. But contrary to the conclusion in Task I where the lower strength level appeared to be relatively immune to hydrogen embrittlement, failure is obtained in a hydrogen environment at the lower hardness levels, only at longer times; i.e., the lower hardness makes these steels less susceptible to hydrogen embrittlement (a well known fact), but not immune.

7.4

No clear cut or consistent advantage exists with either the BPS 4808 or HP1-1 with regard to hydrogen embrittlement susceptibility. The higher strength obtained with the HP1-1 heat treatment does not produce any increased susceptibility that can be directly correlated to an increase in strength.

7.5

To better place the effects in perspective, lowering the hardness from 53HRC to 43HRC is considered to be a major or first order effect. Using VAR instead of ESR is a second order effect by comparison.

7.6

Considering the two grain orientations ranked as a third order effect, the short-transverse is found to be more sensitive to hydrogen embrittlement cracking in 4340 steels than the longitudinal direction. Finally, the choice heat treat method; i.e., BPS 4808 or HP1-1, is considered to be the least significant effect.

7.7

Very little difference exists in ESR or VAR with regard to distortion although the advantage again appears to be with VAR. More significant are the details of the heat treat process, such as the delay time prior to quenching and also the temperature of the quench-tank.

7.8

Measurement of hydrogen in steel remains to be a problem because of inadequate precision and accuracy as was obtained in using commercial laboratories; therefore hydrogen concentration in steel could not be used as a correlation parameter in the analysis.

8.0 RECOMMENDATIONS

8.1

Because of the inherent advantages of 4340 ESR steel with regard to ballistic impact resistance, it becomes advisable to direct a program at improving the resistance of ESR steels to hydrogen embrittlement.

8.2

Since strong evidence now exists that 4340 ESR steel is more susceptible to hydrogen embrittlement than 4340 VAR steel at all hardness levels, consideration should be given to starting ingot chemistries, heat treatment, and possibly surface finish treatments that would increase the resistance of ESR steels to hydrogen embrittlement cracking.

8.3

To quantify the goals, measurements of threshold stress intensities within the framework of fracture mechanics should be made and a target set for 4340 ESR ballistically tolerant steel to attain the same level of resistance as 4340 VAR at a corresponding hardness level.

8.4

Straightening after quenching can be major cause of many of the time delay hydrogen embrittlement service failures because of the introduction of a local residual stress, even though straightening is performed at temperatures just below the final tempering temperature; therefore, more consideration should be given to the processing variables of quench delay time, quench bath temperature, cold stabilization, and multiple tempering, all of which can contribute to distortion and/or residual stresses. These parameters may be more significant that ESR/VAR considerations as regards residual stress induced hydrogen failure.

9.0 ACKNOWLEDGEMENT

The authors acknowledge the cooperative effort of the Watertown Arsenal for the work reported herein, in particular, Mr. Al Anctil's efforts in providing extra test coupons made possible testing beyond that originally planned. The cooperation of Hixson Metal Finishing and NETCO Laboratories also contributed significantly to the success of the test program.

APPENDIX A

Enclosed in this appendix are the three engineering drawings used to machine and heat treat the test coupons.

101780 Notched Round Tensile (NRT) Coupon

101781 Notched Round Bending (NRB) Coupon

101782 Distortion Test Coupon

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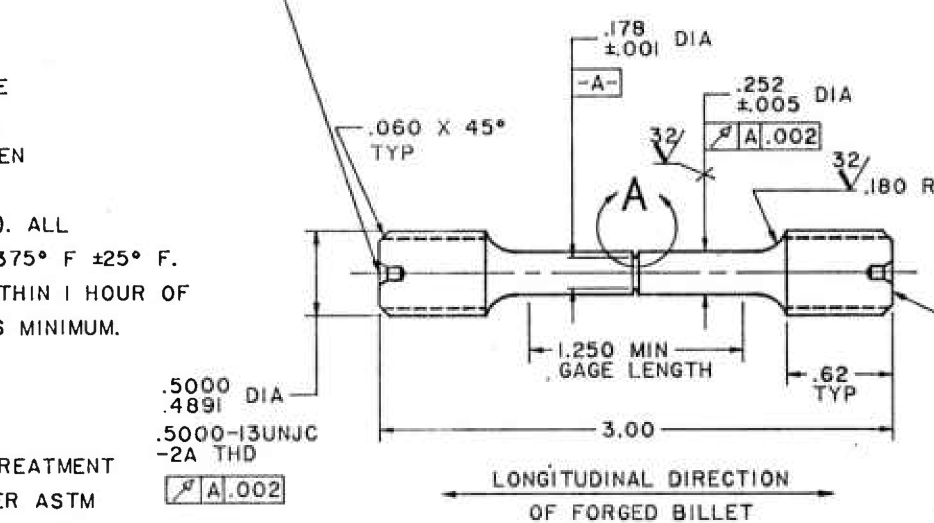

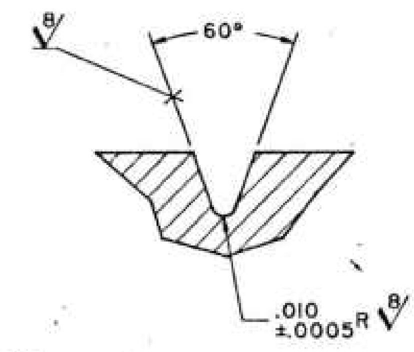

DETAIL A

6. MAGNETIC PARTICLE INSPECT PER MIL-I-6868 (MAGNAGLO).

5. STRESS RELIEF TEMPERATURE AFTER GRIND IS 325° F MAX. FOR -5 AND -11 COUPONS WHEN IN FULLY HEAT TREATED CONDITION (I.E. 290-320 KSI). ALL OTHER THERMAL RELIEF AT 375° F ±25° F. STRESS RELIEF TO BEGIN WITHIN 1 HOUR OF GRINDING, DURATION 3 HOURS MINIMUM.

4. NOTCH TO BE GROUND AFTER HEAT TREATMENT.

3. CHECK FOR CORRECT HEAT TREATMENT RANGE BY R_c CONVERSION PER ASTM A370, TABLE III. FOR REFERENCE :
   - 180-200 KSI = RC 39.6 TO 42.8
   - 260-290 KSI = RC 50.5 TO 53.7
   - 290-320 KSI = RC 53.7 TO 56.6

2 IDENTIFY EACH SPECIMEN BY DASH NUMBER PER BPS 4106, METHOD 2D OR 2DD (VIBRATING PENCIL).

1. ALL SPECIMENS TO BE MACHINED FROM ARMY MATERIALS AND RESEARCH CENTER FURNISHED 4340 STEEL MATERIAL, ADD HEAT NO 8652106.

NOTES :

PART NO. & NAME	MATERIAL	MATERIAL SPEC.	HEAT TREATMENT	FINISH	SH
- 11	4340 VAR	4340 STEEL HEAT NO 3841687	290-320 KSI HP 1-1	OIL	
- 9	4340 VAR		260-290 KSI BPS 4808	OIL	
- 7	4340 VAR		180-200 KSI BPS 4808	OIL	
- 5	4340 ESR	4340 STEEL HEAT NO 3710046	290-320 KSI HP 1-1	OIL	
- 3	4340 ESR		260-290 KSI BPS 4808	OIL	
- 1	4340 ESR		180-200 KSI BPS 4808	OIL	

QUANTITY REQUIRED FOR NOTED ASSY

NEXT ASSY	QTY REQ
COMPLETE ASSY	QTY REQ

UNLESS OTHERWISE SPECIFIED: ALL DIMENSIONS ARE IN INCHES

TOLERANCE ON:

LINEAR DIMENSIONS		ANGLES	
.XXX	= ± .010	XX.XX	= ± 0.50°
.XX	= ± .040	XX.X	= ± 1.0°
.X	= ± .100	XX	= ± 5.0°

DRAWING SYMBOLS & TOLERANCE PER ANSI Y14.5
125 MAX. SURFACE ROUGHNESS PER ANSI B46.1
STRAIGHT THREADS PER MIL-S-8879
MFG PRACTICES PER BMF 5103

DRAWN:	LONG VU	81.12.16
CHECKED:	P. BAKER	82.1.10
STRESS:	BENEKER	82.1.12
APPROVED:	BENEKER	82.1.13

PROJ: AMMRC

Bertea Parker
CONTROL SYSTEMS DIVISION • IRVINE CALIFORNIA

COUPON, NOTCHED ROUND TENSILE (NRT)

SIZE	FSCM NO.	DWG NO.
C	82106	101780

SCALE: 2/1 SHEET 1 OF 1

DWG NO. 101780 SH. 1 REV

DATA BASE-BERTEA CADCAM SYSTEM I

CODE NC

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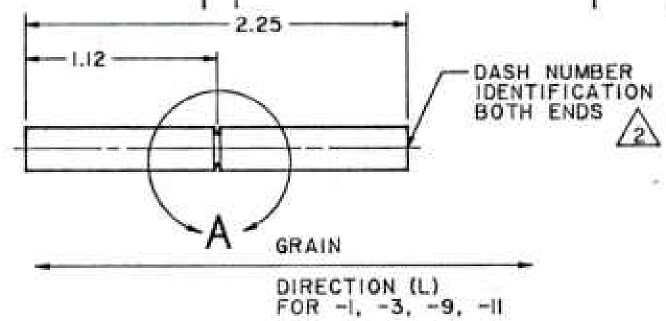
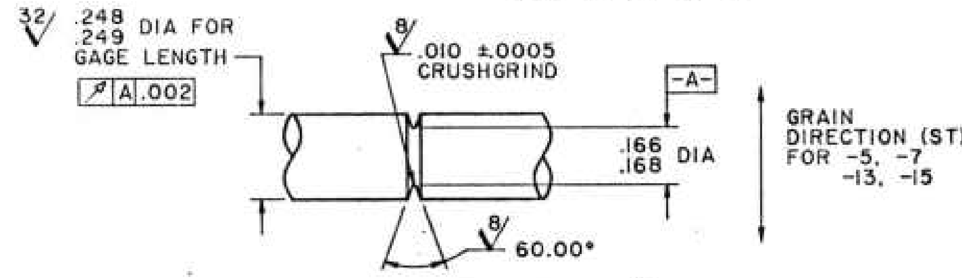




DETAIL A

8. MAGNETIC PARTICLE INSPECT PER MIL-I-6868 (MAGNAGLO).

7 CERTAIN TEST PARTS WILL BE ORDERED WITH CADMIUM PLATING PER QQ-P-416C, CLASS II, TYPE II. FOR SUCH PARTS DO NOT BAKE AFTER PLATING.

6. TEST COUPON IS SIMILAR TO ANSI/ASTM STD F519-77, TYPE IC.

5. STRESS RELIEF TEMPERATURE AFTER GRIND IS 325° F MAX. FOR -3,-7,-11 & -15 COUPON WHEN IN FULLY HEAT TREATED CONDITION (I.E. 290-320 KSI). ALL OTHER THERMAL RELIEF AT 375°±25°F STRESS RELIEF TO BEGIN WITHIN 1 HOUR OF GRINDING, DURATION 3 HOURS MINIMUM.

4. NOTCH TO BE GROUND AFTER HEAT TREATMENT.

3. CHECK FOR CORRECT HEAT TREATMENT RANGE BY R_c CONVERSION PER ASTM A370, TABLE III. FOR REFERENCE :
   260-290 KSI = RC 50.5 TO 53.7
   290-320 KSI = RC 53.7 TO 56.6

2 IDENTIFY EACH SPECIMEN BY DASH NUMBER PER BPS 4106, METHOD 2D OR 2DD (VIBRATING PENCIL).

1. ALL SPECIMENS TO BE MACHINED FROM ARMY MATERIALS AND RESEARCH CENTER FURNISHED 4340 STEEL MATERIAL, AOD HEAT NO 8652106.

NOTES :

PART NO. & NAME	MATERIAL	MATERIAL SPEC.	HEAT TREATMENT	FINISH	SH
- 15	4340 VAR (TRANS.)	4340 STEEL HEAT NO 3841687	290-320 KSI HP 1-1	OIL	
- 13	4340 VAR (TRANS.)		260-290 KSI BPS 4808		
- 11	4340 VAR (LONG.)		290-320 KSI HP 1-1		
- 9	4340 VAR (LONG.)		260-290 KSI BPS 4808		
- 7	4340 ESR (TRANS.)	4340 STEEL HEAT NO 3710046	290-320 KSI HP 1-1		
- 5	4340 ESR (TRANS.)		260-290 KSI BPS 4808		
- 3	4340 ESR (LONG.)		290-320 KSI HP 1-1	7	
- 1	4340 ESR (LONG.)		260-290 KSI BPS 4808		

QUANTITY REQUIRED FOR NOTED ASSY

NEXT ASSY	QTY REQ
COMPLETE ASSY	QTY REQ

UNLESS OTHERWISE SPECIFIED: ALL DIMENSIONS ARE IN INCHES

TOLERANCE ON:

LINEAR DIMENSIONS		ANGLES	
.XXX	= ± .010	XX.XX	= ± 0.50°
.XX	= ± .010	XX.X	= ± 1.0°
.X	= ± .100	XX	= ± 5.0°

DRAWING SYMBOLS & TOLERANCE PER ANSI Y14.5
125 MAX. SURFACE ROUGHNESS PER ANSI B46.1
STRAIGHT THREADS PER MIL-S-8879
MFG. PRACTICES PER BMF 5103

DRAWN:	LONG VU	81.12.16
CHECKED:	P. BAKER	82.1.10
STRESS:	BENEKER	82.1.12
APPROVED:	BENEKER	82.1.13

PROJ: AMMRC

Bertea Parker
CONTROL SYSTEMS DIVISION • IRVINE CALIFORNIA

COUPON-NOTCHED ROUND BENDING (NRB)

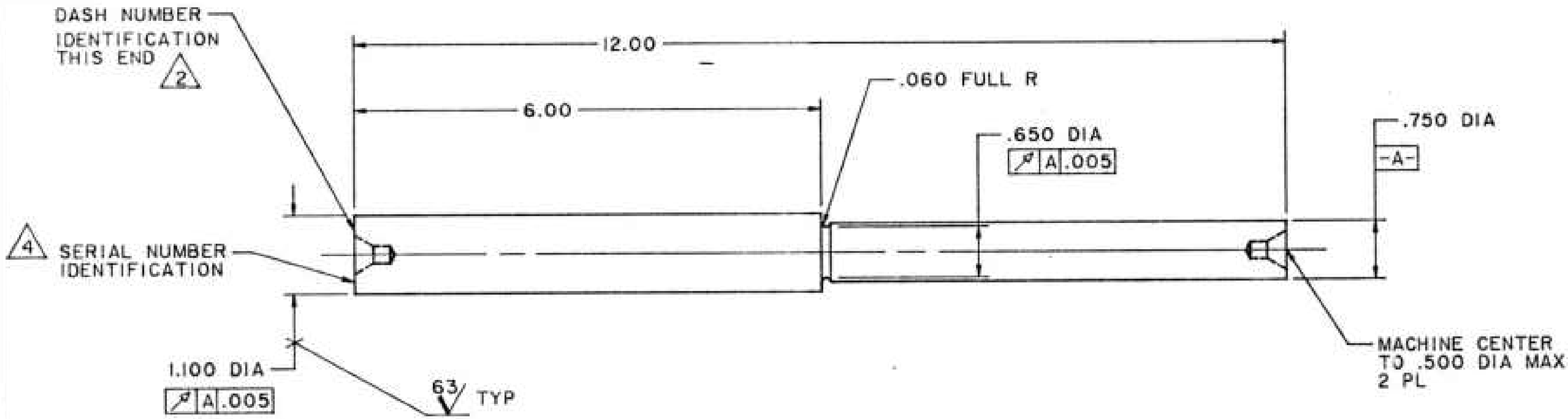
SIZE	FSCM NO.	DWG NO.
C	82106	101781
SCALE: 2/1		SHEET 1 OF 1

DWG NO. 101781 SH. 1 REV

DATA BASE-BERTEA CADCAM SYSTEM

CODE NC

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



5. MAGNETIC PARTICLE INSPECT PER MIL-I-6868 (MAGNAGLO).

4. SERIALIZE CONSECUTIVELY FOR EACH DASH NUMBER. (I.E. 1 THRU 20) USE BPS 4106, METHOD 2D OR 2DD.

3. THESE TEST PARTS MEASURE HEAT TREAT DISTORTION. THEREFORE, NO STRAIGHTENING ALLOWED AFTER QUENCH OR TEMPERING.

2. IDENTIFY EACH SPECIMEN BY DASH NO. PER BPS 4106, METHOD 2D OR 2DD (VIBRATING PENCIL).

1. ALL SPECIMENS TO BE MACHINED FROM ARMY MATERIALS AND RESEARCH CENTER FURNISHED 4340 STEEL MATERIAL, AND HEAT NO.8652106.

NOTES :

PART NO. & NAME	MATERIAL	MATERIAL SPEC.	HEAT TREATMENT	FINISH	SH
-3	4340 VAR	4340 STEEL HEAT NO. 3841687	260-290 KSI BPS 4808	OIL	
-1	4340 ESR	4340 STEEL HEAT NO. 3710046	260-290 KSI BPS 4808	OIL	

QUANTITY REQUIRED FOR NOTED ASSY	
NEXT ASSY	QTY REQ
COMPLETE ASSY	QTY REQ

UNLESS OTHERWISE SPECIFIED: ALL DIMENSIONS ARE IN INCHES

TOLERANCE ON:

LINEAR DIMENSIONS		ANGLES	
.XXX	= ± .010	XX.XX	= ± 0.50°
.XX	= ± .040	XX.X	= ± 1.0°
.X	= ± .100	XX	= ± 5.0°

DRAWING SYMBOLS & TOLERANCE PER ANSI Y14.5
125 MAX. SURFACE ROUGHNESS PER ANSI B46.1
STRAIGHT THREADS PER MIL-S-8879
MFG. PRACTICES PER BMF 5105

DRAWN:	LONG.VU	81.12.17
CHECKED:	P. BAKER	82.1.10
STRESS:	BENEKER	82.1.12
APPROVED:	BENEKER	82.1.13

PROJ: AMMRC

Bertea Parker
CONTROL SYSTEMS DIVISION • IRVINE CALIFORNIA

COUPON, DISTORTION TEST

SIZE	FSCM NO.	DWG NO.
C	82106	101782
SCALE: 1 /1		SHEET 1 OF 1

DWG. NO. 101782 SH. 1 REV

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Final Report 20 Apr 81 to 20 Jul 82

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Key Words
Hydrogen Embrittlement
4340 Steel
Heat treatment
Helicopters
Potentiostatic Techniques
Mechanical Properties
ESR Steel
Distortion

A test program to compare the relative hydrogen embrittlement susceptibility of remelted 4340 steel with ESR and VAR methods has been completed. The issue of ESR's susceptibility to hydrogen embrittlement arose when unexpected difficulties were experienced with critical control system actuator pistons on the helicopter programs. High strength (above 260 Ksi) 4340 ESR steel is used in these applications because of 4340 ESR's demonstrated superior ballistic tolerance. Three heat treat levels and two grain orientations were evaluated. Three test methods were applied to measure embrittlement susceptibility. A significant reduction in embrittlement susceptibility is associated with lower strength (~43 HRC) as compared to high strength (~53 HRC) 4340. The short transverse grain direction is more susceptible than the longitudinal direction, and all test methods indicated that VAR is less susceptible to hydrogen embrittlement than ESR. A parallel effort during the test program focused on heat treat distortion differences between ESR and VAR 4340. While a difference in distortion propensity cannot be ruled out on the basis of test results, it can be concluded that such differences between ESR and VAR are small compared to heat treatment parameters affecting distortion.

Watertown, Massachusetts 02172
EVALUATION OF THE RELATIVE HYDROGEN
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AND ITS HEAT TREAT DISTORTION PROPERTIES
L. Raymond and C. Beneker
Parker Hannifin Corporation
Bertea Control Systems Division
Irvine, California 92715
Final Technical Report AMMRC TR 82-49
September 1982, 47 pp
Contract UAAG46-81-C-U045
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